Wind Profile Parameters and Turbulence Intensity Over Several Roughness Element Geometries

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ABSTRACT

ESTIMATING equations were developed for the mean velocity profile parameters (Z_o, u_{*o}, and D) in the logarithmic law and for longitudinal turbulence intensity ($\sigma_u/\overline{u}_z$). The estimates were based on wind tunnel measurements over several roughness element shapes, sizes, heights, and geometrical patterns. All the prediction equations had correlation coefficients > 0.90. These equations have application in wind erosion of soil particles, water evaporation, and transport of gases. They only apply to a particular set of conditions, which indicates a need for more universally applicable equations for the profile parameters and turbulence intensity.

INTRODUCTION

Knowledge concerning mean and turbulent wind flow properties near the surface is essential because they influence the exchange of mass, heat, and momentum between the boundary and the environment, like erosion of soil particles, evaporation of water, and transport of gases.

Much information has accumulated about the wind profile in the boundary layer, both in the atmosphere and in wind tunnels.

For aerodynamically rough atmospheric flows in the "constant stress" layer, the following form of the logarithmic law is most often used to describe the mean velocity profile:

$$\overline{u}_z = \frac{u_*}{k}\left[\ln\left(\frac{Z - D}{Z_o}\right) + \Phi_{(z)}\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad [1]$$

where $\overline{u_z}$ is the mean velocity at height z from some reference plane; u_* is the friction velocity defined as $(\tau_o/\rho)^{1/2}$, where τ_o is the shear stress at the surface and ρ is air density, k is von Karman's constant (0.4); D is an "effective" height of roughness; Z_o is a roughness parameter, and $\Phi_{(z)}$ is the integral diabatic influence function. The function, $\Phi_{(z)}$ is zero for adiabatic conditions, which include most wind tunnel flows. We are primarily interested in soil erosion by wind, which generally occurs in favorable pressure gradients with various degrees of roughness at the surface and in flows with high velocity and turbulence. For those conditions, near the surface, we can safely assume $\Phi_{(z)} = 0$.

Almost without exception, those who have reported on wind-tunnel, rough-boundary flows have noted the uncertainty in determining the origin for the coordinate normal to the boundary (denoted Z here). Perry et al. (1968) called the distance below the roughness height (h) to the point where $\overline{u}_z = 0$ an error in origin ε. Reported average ε values have varied from 0.67 to 0.75h (Moore, 1951; Perry et al., 1968). In terms of the parameters in equation [1]:

$$\epsilon = h - (D + Z_o) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad [2]$$

In cases where the roughness elements are of nonuniform height or flexible (vegetation), h would be difficult to specify. If the origin for Z is at the base of the roughness elements, the term ($D + Z_o$) is usually called the displacement height, the distance from the origin to the point where the mean velocity profile extrapolates to zero.

Several writers have published equations for determining Z_o for particular cases (Cowan, 1968; Counihan, 1971; Lettau, 1969; Thom, 1971; Szeicz, 1969). Few have attempted to relate u_* and turbulence intensity to roughness element geometry. We present several regression-type equations for predicting Z_o, u_*, D, and longitudinal turbulence intensity ($\sigma_u/\overline{u}_z$) for a limited number of roughness element patterns and attempt to correlate our results with those of earlier workers.

EXPERIMENTAL PROCEDURE

In recent years, we have measured several wind tunnel mean velocity and turbulence profiles over various surfaces in several studies related to wind erosion (Lyles and Allison, 1976; Lyles et al., 1974). Most data involved right cylinders with their vertical axis normal to the boundary in several height-spacing combinations. Other roughness elements were closely packed spheres, irregular shaped gravel, and sand.

The wind-tunnel facility (1.52 m wide, 1.93 m high, and 16.46 m long) was a recirculating push-type with freestream longitudinal-turbulence intensity of 1.7 percent. The entire floor length was occupied by the roughness elements, and mean windspeed and turbulence intensity were obtained from vertical traverses located 14.46 m downstream with a pitot-static tube and constant-temperature hotwire anemometer, respectively, with appropriate transducers, signal conditioners, and recorders. The mean velocity-profile parameters (Z_o, u_*, D) were calculated from

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windspeed measurements taken above the roughness elements in the lower 10 to 20 percent of the boundary layer using the adiabatic form of equation [1]. This generally involved six to ten heights and, in some cases, three to five replications at each height. We are defining the boundary layer depth, δ, as the height Z where $\bar{u}_Z = 0.99\ \bar{u}_\infty$ and $\bar{u}_\infty$ is the free-stream mean velocity.

EXPERIMENTAL DATA AND OBSERVATIONS

Many "independent" variables and combinations of variables that characterize the roughness elements (number, height, diameter, etc.) were correlated with the dependent variables (Z_o, u_*, D, and $\sigma_u/\bar{u}_Z$) using selected variables and stepwise multiple regression where variables were entered in the order of their greatest contribution to variance.

Roughness Parameter, Z_o

Several published equations for the roughness parameter, Z_o, are of the form (Cowan, 1968; Szeicz, 1969; Thom, 1971):

$$Z_o = \lambda h^n \quad \ldots \quad [3]$$

where h is average roughness height, and λ and n are constants with different values for particular cases. For equilibrium flows, Counihan (1971) included a term for the proportion of surface area occupied by the roughness elements:

$$Z_o = (1.08\ A_r/A - 0.08)h,\ 0.10 \leqslant A_r/A \leqslant 0.25 \quad \ldots \quad [4]$$

where A_r is the plan surface area of roughness elements, and A is the total plan surface area. In equation [4], $\lambda = 1.08\ A_r/A - 0.08$ and $n = 1$.

Lettau (1969) suggested this equation for Z_o:

$$Z_o = 0.5\ hA_sN/A \quad \ldots \quad [5]$$

where A_s is the average silhouette (frontal) area of the roughness elements, and N/A is the number of roughness elements per unit area. Equation [5] expressed in terms of equation [3] would have $\lambda = 0.5\ A_sN/A$ and $n = 1$. For standing circular cylinders, equation [5] becomes:

$$Z_o = 0.5\frac{h^2 d_s}{L_xL_y} \quad \ldots \quad [6]$$

where d_s is average cylinder diameter (silhouette); L_x is the center-to-center distance between cylinders in the flow direction; and L_y the corresponding distance normal to flow direction.

To obtain high correlation coefficients, we separated the cylinder data into two height categories to generate these equations:

$$\hat{Z}_o = 0.32\frac{h^{0.96}\ d_s^{0.29}}{L_x^{0.44}\ L_y^{0.94}},\ 0 < h \leqslant 4\ \text{cm},\ R = 0.94,\ \text{and} \quad \ldots \quad [7]$$

$$\hat{Z}_o = 971\frac{h^{1.08}\ d_s^{1.82}}{L_x^{2.32}\ L_y^{1.86}},\ 4 < h < 43\ \text{cm},\ R = 0.96. \quad \ldots \quad [8]$$

In equation [7], d_s ranged between 0.28 and 1.59 cm and L_x and L_y between 2.54 and 20.32 cm; in equation [8], d_s ranged between 0.28 and 2.54 cm and L_x between 10.16 and 60.96 cm, and L_y between 10.16 and 30.48 cm.

For closely packed sand grains and closely packed smooth spheres, we found the equation of Nikuradse (1950) was adequate:

$$Z_o = 0.033\ d_p \quad \ldots \quad [9]$$

where d_p is particle diameter.

Friction Velocity, u_*

Because u_* varies with mean velocity, we chose 894 cm/s freestream velocity ($\bar{u}_\infty$) as a standard and denoted u_{*o} as the u_* associated with that standard. Again, separating the cylinder data in two height categories, we obtained:

$$\hat{u}_{*o} = 68.66\frac{h^{0.13}\ d_s^{0.05}}{L_x^{0.07}\ L_y^{0.15}},\ 0 < h \leqslant 4\ \text{cm},\ R = 0.92,\ \text{and} \quad \ldots \quad [10]$$

$$\hat{u}_{*o} = 165.5\frac{h^{0.08}\ d_s^{0.21}}{L_x^{0.28}\ L_y^{0.22}},\ 4 < h < 43\ \text{cm},\ R = 0.96 \quad \ldots \quad [11]$$

with the same restrictions on d_s, L_x, and L_y as for Z_o.

Effective Height, D

Using all the cylinder data, we obtained this equation for effective height D:

$$\hat{D} = 0.839\ h - 1.182,\ 0.4 < h \leqslant 43\ \text{cm},\ r = 0.99 \quad \ldots \quad [12]$$

Although equation [12] has a high simple correlation coefficient, values of $h > 1.4$ cm give negative values for D, which is mathematically correct but is physically impossible, if $D + Z_o$ is negative (a finite windspeed below the surface). Other combinations of h, d_s, L_x, and L_y did not improve the equation.

Turbulence Intensity, $\sigma_u/\bar{u}_Z$

Regression equations for the local longitudinal turbulence intensity at a reference height equal to $(Z - D)/\delta = 0.05$ (δ is the boundary layer depth) were:

$$\hat{\sigma_u/\bar{u}_Z} = 42.7\frac{h^{0.21}\ d_s^{0.05}}{(L_xL_y)^{0.17}},\ 0 < h \leqslant 4\ \text{cm},\ R = 0.91,\ \text{and} \quad \ldots \quad [13]$$

$$\hat{\sigma_u/\bar{u}_Z} = 227.5\frac{h^{0.20}\ d_s^{0.50}}{L_x^{0.49}\ L_y^{0.42}},\ 4 < h < 43\ \text{cm},\ R = 0.94 \quad \ldots \quad [14]$$

TABLE 1. COMPARISONS OF ROUGHNESS PARAMETERS (Z_o) COMPUTED FROM EQUATIONS [7] OR [8] WITH THOSE COMPUTED FROM EQUATIONS OF LETTAU (1969) AND COUNIHAN (1971) FOR 15 CASES

Case no.	h, cm	d_s,cm	L_x,cm	L_y,cm	Z_o Eq. [6] (Lettau), cm	Eq. [7] or Eq. [8], cm	Eq. [4] (Counihan), cm
1	0.5	0.655	5.08	5.08	0.00317	0.01544	−0.03295
2	2.5	0.655	5.08	5.08	0.07932	0.07241	−0.16475
3	2.5	0.655	2.54	10.16	0.07932	0.05120	−0.16475
4	2.5	0.655	10.16	2.54	0.07932	0.10240	−0.16475
5	2.5	0.278	10.16	2.54	0.03366	0.07987	−0.19365
6	5.0	0.655	10.16	10.16	0.07932	0.15807	−0.38237
7	10.0	0.278	20.32	20.32	0.03366	0.00387	−0.79841
8	20.0	1.589	60.96	15.24	0.34208	0.02610	−1.55389
9	43.0	2.54	30.48	30.48	2.52761	0.19276	−3.18671
10	1.0	0.655	2.54	2.54	0.05076	0.10343	−0.02359
11	1.0	1.589	5.08	5.08	0.03079	0.03885	0.00299
12	0.1	0.28	20.32	20.32	0.000003	0.00038	−0.00798
13	25.4	0.28	15.24	2.54	2.33333	1.00173	−1.98836
14	43.0	2.54	76.2*	30.48	1.01105	0.02299	−3.33868
15	2.5	1.589	2.54	2.54	0.76967	0.24368	0.62992

*Outside range of experimental data.

with the same restrictions on d_s, L_x, and L_y as for the other parameters.

INTERPRETATION AND DISCUSSION

Roughness Parameters, Z_o

Values of Z_o calculated with equation [7] or [8] for several selected height-size-spacing combinations occasionally agreed with Lettau's equation [5] but seldom agreed with Counihan's equation [4] (Table 1). Neither Lettau's nor Counihan's equation discriminated among geometrical patterns of roughness elements with the same number of elements per area. For example, cases 2, 3, and 4 in Table 1 all have equal values for height, size, and number of elements per area but different geometrical patterns or distributions—case 2, uniform spacing; case 3 in rows parallel to flow direction; and case 4 in rows normal to flow direction. With equation [7], different values for Z_o were calculated for the three cases, whereas with Lettau's and Counihan's equations, the same Z_o value was calculated for all cases. Except for two cases, Counihan's equation gave negative Z_o values (Table 1). Most of the examples, however, had A_r/A values far greater than the limitations specified for his equation. The only cases with positive Z_o values were for 11 with an A_r/A value of 0.077, slightly lower than the minimum limit (0.10), and 15, with A_r/A value of 0.307, slightly larger than the maximum limit (0.25). Of course, equation [7] or [8] is also restricted to the range of experimental data used in developing them and it would be difficult to apply to roughness elements of nonuniform cross-section (both frontal and plan views). Unfortunately, regression equations can seldom be extrapolated and almost never include all the range of independent variables that may influence the dependent variable in question—in our case, all the possible shapes, heights, concentrations, and patterns of roughness elements that influence the roughness parameter, Z_o. Consequently, published equations for Z_o apply only to particular cases, and we are only adding to that number and must wait future development of more universally applicable equations.

Roughness parameters computed with Nikuradse's equation [9] for closely packed elements showed fair to good agreement (r = 0.93) with those determined from mean velocity profile measurements (Table 2). The higher values from velocity profiles over gravel suggest that shape irregularity and smoothness

TABLE 2. ROUGHNESS PARAMETERS (Z_o) DERIVED FROM MEAN VELOCITY PROFILES AND COMPUTED FROM NIKURADSE'S (1950) EQUATION OVER CLOSELY PACKED PARTICLES

Kind of particle	d_p, cm	Z_o Eq. [9] (Nikuradse), cm	Profile, cm	Source
Spheres	0.41	0.0137	0.0080	Schlichting (1960)
Spheres (tapioca)	0.61	0.0202	0.0189	Lyles (1971)
Spheres (glass)	1.64	0.0547	0.0499	Lyles (1971)
Spheres (glass)	2.45	0.0818	0.0988	Lyles (1971)
Gravel	0.238-0.283	0.0087	0.0328	Chowdhury (1966)
Gravel	0.200-0.332	0.0089	0.0293	Lyles
Gravel	0.635-0.952	0.0265	0.0543	Lyles
Sand (smoothed)	0.015-0.029	0.0007	0.0007 ± 0.00047*	Lyles
Sand (smoothed)	0.042-0.059	0.0017	0.0009 ± 0.00040*	Lyles
Sand	0.015-0.025	0.0007	0.00046	Zingg (1953)
Sand	0.025-0.030	0.0009	0.00137	Zingg (1953)
Sand	0.030-0.042	0.0012	0.00274	Zingg (1953)
Sand	0.042-0.059	0.0017	0.00366	Zingg (1953)
Sand	0.059-0.084	0.0024	0.00487	Zingg (1953)

*Average of 15 profiles.

TABLE 3. FRICTION VELOCITIES (u_{*o}) DERIVED FROM MEAN VELOCITY PROFILES AND COMPUTED FROM EQUATION [15] OVER CLOSELY PACKED PARTICLES. PROFILE DATA, EXCEPT FOR SMOOTHED SAND AND LAST 5 ROWS, WERE USED TO DERIVE EQUATION [15]

		u_{*o}	
Kind of particle	d_{p},cm	Profile, cm/s	Eq. [15], cm/s
Sand	0.010-0.012	28.68	29.43
Sand (smoothed)	0.015-0.030	28.46	31.61
Sand	0.021-0.025	31.27	31.68
Sand	0.042-0.047	34.30	33.84
Sand (smoothed)	0.042-0.059	29.73	34.27
Sand	0.078-0.084	35.60	35.93
Gravel	0.200-0.332	41.30	40.47
Gravel	0.635-0.952	44.70	45.14
Spheres (tapioca)	0.606	44.50	43.94
Spheres (glass)	1.641	47.50	48.55
Spheres (glass)	2.453	50.70	50.54
Sand	0.015-0.025	25.63*	31.24
Sand	0.025-0.030	28.60*	32.25
Sand	0.030-0.042	32.65*	33.13
Sand	0.042-0.059	31.85*	34.27
Sand	0.059-0.084	36.41*	35.49

*Calculated from Zingg's (1953) velocity profile data.

besides average diameter affect Z_O. In determining his velocity profile Z_O values, Zingg (1953) used a graphical technique, which is subject to large errors and which could account for his larger profile values for four of five cases.

Although we used current measuring and recording instrumentation, Z_O values computed from velocity profiles over the same surface varied greatly as indicated by the data over the smoothed sand surfaces in Table 2. There was a 5- to 6-fold difference between minimum and maximum values of Z_O obtained from the 15 profiles over the same surfaces. Such variability complicates interpreting data and identifying factors affecting Z_O. Effects of upwind distance (fetch) on any of the parameters have not been considered. For the shorter elements, mean velocity and turbulence were measured more than 360 times the height of elements downwind; for the taller elements, these parameters were measured between 34 and 285 times the height of the elements downwind.

Friction Velocity, u_*

Perhaps the most interesting profile parameter is the friction velocity, u_*, which indicates the wind's capacity to transport soil and characterizes the turbulence of the flow. Equations [10] and [11] cannot be extrapolated much beyond the height-spacing-size data used in their development. Equation [10] cannot be used for closely packed spheres because predicted values increase as particle diameter decreases. Logically, one would look for an equation of the Nikuradse form to predict u_{*O} over closely packed particles. Based on profile-derived values of u_{*O} over sand, gravel, and spheres, this equation

$$\hat{u}_{*o} = 46.2(d_p)^{1/10},\ 0 < d_p \leq 2.54 \text{ cm} \quad \ldots\ldots\ldots\ldots\ [15]$$

has a very high simple correlation coefficient (0.99) (Table 3), where d_p is the average particle diameter. Two cases in Table 3 indicated mechanical smoothing of sand grains results in lower profile values of u_{*O}. Comparisons with Zingg's profile data indicated predicted values of u_{*O} were within 2 to 20 percent

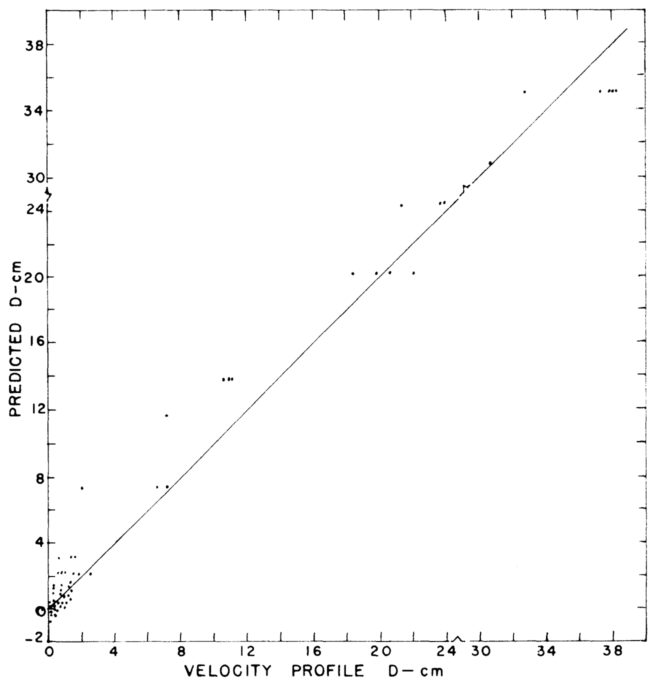

FIG. 1 Comparison between profile-derived "effective height" [D] and that predicted by equation [12]. For clarity, only a selected number of D values < 3 cm are plotted.

in Table 3. Friction velocity values derived from measured mean velocity profiles over identical surfaces may vary considerably, depending on number of replications, number of vertical data points considered and their relation to boundary layer depth, and precision of flow generating, measuring, and recording equipment.

Also, remember that u_{*O} is associated with a freestream velocity ($\bar{u}_\infty$) of 894 cm/s. If friction velocities are desired for other $\bar{u}_\infty$'s, this simple equation may be used:

$$(u_*)_V = u_{*o} \frac{(\bar{u}_\infty)_V}{894} \quad \ldots\ldots\ldots\ldots\ [16]$$

where $(\bar{u}_\infty)_V$ is the freestream velocity in question.

Effective Height, D

A simple regression equation [12] correlates 124 D values, obtained from mean velocity profiles, with a coefficient of 0.99. The distribution of the data may partially explain this. About 80 percent of the D values used in the regression analysis were < 3 cm; most were < 1 cm. About 66 percent of the D values < 3 cm were underestimated by equation [12], but the deviations in magnitude are generally small and could explain the high correlation coefficient (Fig. 1).

For our short cylinder data (h < 4 cm), ϵ/h averaged 0.65, which compared favorably with Perry's (1968) results, but obviously ϵ/h is not a constant when considering taller roughness elements—decreasing as height increases (Fig. 2). In our case, however, the displacement height is an artifact of applying the log law to velocity measurements obtained above roughness elements and the interheight velocities (those below the point where the mean velocity profile extrapolates to zero) are, in fact, > 0.

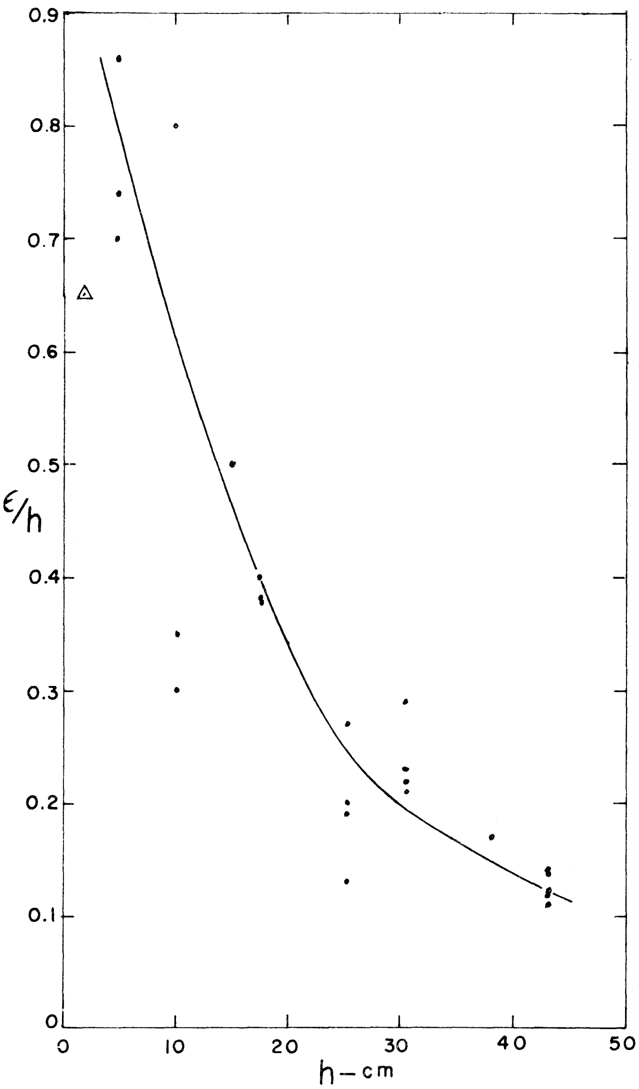

FIG. 2 "Error" in origin of the vertical coordinate as related to roughness element height [h]. The triangular symbol (Δ) is the average for all the short cylinders.

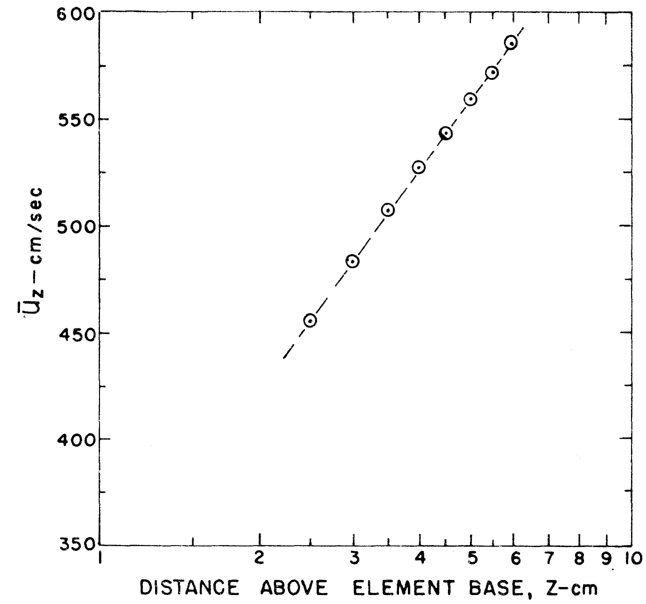

FIG. 3 Example of predicted mean velocity profile over short cylinders: h = 2 cm, d_s = 0.655 cm, L_x = L_y = 5.08 cm at a freestream velocity of 894 cm/s using equations [7], [10], and [12] for Z_o, u_{*o}, and D, respectively, in the log law.

Turbulence Intensity, $\sigma_u/\bar{u}_z$

Equation [13] does not apply for closely packed spheres, predicting larger values of $\sigma_u/\bar{u}_z$ as sphere diameter (d_p) decreases, but actual (measured) values, as expected, increased with sphere diameter. From limited data, we obtained this equation for closely packed particles:

$$\widehat{\sigma_u/\bar{u}_z} = 25.0\, d_p^{0.148},\ 0 < d_p < 2.54 \text{ cm},\ r = 0.99 \ldots\ldots \quad [17]$$

where d_p is particle diameter, and the reference height is $(Z - D)/\delta = 0.05$. Table 4 indicates the "goodness of fit" for equation [17] (first 5 rows). Equation [17] underpredicted the turbulence intensity over gravel, suggesting that particle shape and smoothness influence turbulence.

General

One could use equations [7], [10], and [12] in the adiabatic form of equation [1] to generate a mean velocity profile in the "constant stress" layer for selected height-size-pattern combinations of roughness elements (Fig. 3). Using the roughness element data of Fig. 3 in equation [13] gave $\sigma_u/\bar{u}_z$ = 27.8 percent for $(Z - D)/\delta = 0.05$. For our wind tunnel, $\delta \cong 44$ cm for the data in question, which gave Z = 2.7 cm and $\bar{u}_z \cong 467$ cm/s from Fig. 3. Then, $\sigma_u/u_{*o} = 2.52$, which agreed closely with the mean value reported by Counihan (1975) and was only slightly larger than an average value we reported earlier (Lyles et al., 1971). Such agreement supports the prediction equations reported here and mean velocity profiles computed from combining them in the log law.

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TABLE 4. LONGITUDINAL TURBULENCE INTENSITY ($\sigma_u/\bar{u}_z$) MEASURED OVER CLOSELY PACKED PARTICLES AND COMPUTED FROM EQUATION [17] AT A REFERENCE HEIGHT OF $(Z - D)/\delta = 0.05$

Kind of particle	d_p,cm	$\sigma_u/\bar{u}_z$ Measured, percent	$\sigma_u/\bar{u}_z$ Eq. [17] percent
Sphere (tapioca)	0.606	22.53*	23.21
Sphere (glass)	1.641	27.09*	26.90
Sphere (glass)	2.453	29.20*	28.55
Sand	0.015-0.030	14.96*	14.30
Sand	0.042-0.059	15.43*	16.09
Gravel	0.200-0.332	24.49	20.55
Gravel	0.635-0.953	29.16	24.16

*Data used in deriving equation [17].

Wind Profile Parameters

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